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Thermal Plasma Gasification
of Municipal Solid Waste (MSW)

Youngchul Byun, Moohyun Cho, Soon-Mo Hwang and Jaewoo Chung

Additional information is available at the end of the chapter

1. Introduction

Rapid economic development has led to an annual increase in municipal solid waste (MSW) production. According to the US Environmental Protection Agency (US EPA), MSW generation has increased by a factor of 2.6 since 1960 [1]. The US EPA endorsed the concept of integrated waste management that could be tailored to fit particular community's needs. Sustainable and successful treatment of MSW should be safe, effective, and environmentally friendly. The primary components of the philosophy are (a) source reduction including reuse of products and on-site composting of yard trimmings, (b) recycling, including off-site (or community) composting, (c) combustion with energy recovery, and (d) disposal through landfill. Among them, landfill has been the practice most widely adopted. There are two main drawbacks of landfill. One is that surrounding areas of landfills are often heavily polluted since it is difficult to keep dangerous chemicals from leaching out into the surrounding land [2]. The other is that landfill can increase chances of global warming by releasing CH_4, which is 20 times more dangerous as a greenhouse gas than CO_2. Therefore, we must find a more environmentally friendly alternative to treat MSW.

A plasma is defined as a quasineutral gas of charged and neutral particles which exhibits collective behavior [3]. Plasma can be classified into non-thermal and thermal plasmas according to the degree of ionization and the difference of temperature between heavy particles and electrons [4, 5]. Thermal plasma can be characterized by approximate equality between heavy particle and electron temperatures and have numerous advantages including high temperature and high energy density [6]. Electrically generated thermal plasma can reach temperature of ~10,000 °C or more, whereas only an upper temperature limit of 2,000 °C can be achieved by burning fossil fuels [7]. For this reason, thermal plasma has been traditionally used in high temperature and large enthalpy processes [8-11].

Thermal plasma technology has been applied in various industrial applications such as cutting, welding, spraying, metallurgy, mass spectroscopy, nano-sized particle synthesis,

powder spheroidization, and waste treatment [12-15]. Over the past decade, thermal plasma process has also been regarded as a viable alternative to treat highly toxic wastes, such as air pollutant control (APC) residues, radioactive, and medical wastes [16-25]. It has also been demonstrated that the thermal plasma process is environmentally friendly, producing only inert slag and minimal air pollutants that are well within regional regulations. Recently, a thermal plasma process for a gasification of MSW has been planned and constructed as a pilot program in commercial plants. The thermal plasma process employs extremely high temperatures in the absence or near-absence of O_2 to treat MSW containing organics and other materials. The MSW is dissociated into its constituent chemical elements, transformed into other materials some of which are valuable products. The organic components are transformed into syngas, which is mainly composed of H_2 and CO and inorganic components are vitrified into inert glass-like slag.

We constructed thermal plasma plants for the recovery of high purity H_2 (> 99.99%) from paper mill waste at 3 TPD (ton/day) and the gasification of MSW at 10 TPD [26, 27]. For the recovery of high purity H_2, gases emitted from a gasification furnace equipped with a non-transferred thermal plasma torch were purified using a bag-filter and wet scrubber. Thereafter, the gases, which contained syngas, were introduced into a H_2 recovery system, consisting largely of a water gas shift (WGS) unit for the conversion of CO to H_2 and a pressure swing adsorption (PSA) unit for the separation and purification of H_2. It was successfully demonstrated that the thermal plasma process for solid wastes gasification, combined with the WGS and PSA, produced high purity H_2 (20 Nm^3/hr (400 H_2-Nm^3/ton), up to 99.99%) using a plasma torch that used 1.6 MWh/ton of electricity. For the treatment of MSW, we developed a gasification commercial plant for the direct treatment of municipal solid waste (MSW) with a capacity of 10 TPD, using an integrated furnace equipped with two non-transferred thermal plasma torches. It was successfully demonstrated that the thermal plasma process converted MSW into innocuous slag, with much lower levels of environmental air pollutant emissions and the syngas (287 Nm^3/ton for H_2 and 395 Nm^3/ton for CO), using 1.14 MWh/ton of electricity (thermal plasma torch (0.817 MWh/ton) + utilities (0.322 MWh/ton)) and 7.37 Nm^3/ton of liquefied petroleum gas (LPG).

Such a plant is currently operating in Cheongsong, Korea. The 3.5 years' worth of data obtained from this plant has given us the insight into the economics and design parameters for extending capacity to 100 TPD. In this chapter, we describe the past operational performances of 10 TPD thermal plasma gasification plant for MSW treatment, evaluate the economics, and suggest the design parameters for extending capacity to 100 TPD with brief discussion on recent achievements in thermal plasma technology for the treatment of solid wastes on the basis of selected scientific and technical literatures.

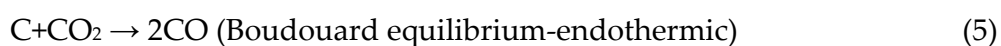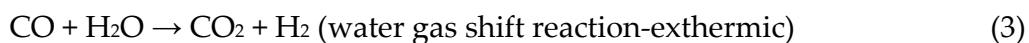## 2. Characteristics of thermal plasma process for the treatment of solid wastes

Thermal plasma for wastes treatment has received great attention recently to meet the contemporary needs to solve problems with increasing environmental pollutions.
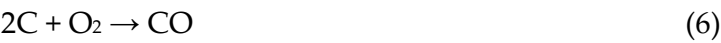
Compared with commonly used combustion methods for waste treatment, thermal plasma provides the following advantages; (1) high energy density and temperatures, and the correspondingly fast reaction times, offer the potential for a large throughput with a small furnace. (2) High heat flux densities at the furnace boundaries lead to fast attainment of steady state conditions. This allows rapid start-up and shutdown times compared with other thermal treatments such as incineration. (3) Only a small amount of oxidant is necessary to generate syngas, therefore, the gas volume produced is much smaller than with conventional combustion processes and so is easier and less expensive to manage. These characteristics make thermal plasma process an ideal alternative to conventional methods of solid waste treatment.

There are three kinds of processes inside the thermal plasma furnace for solid waste treatment. First is pyrolysis (without O_2) of gaseous, liquid, and solid waste in a thermal plasma furnace with plasma torches. Second is gasification (O_2-starved) of solid waste containing organic compounds to produce syngas ($H_2 + CO$). Last is vitrification of solid wastes by transferred, non-transferred, or hybrid arc plasma torch according to electric conductivity of substrate. Processes being considered importantly for the treatment of solid wastes are gasification and vitrification; this is due to the energy recovery and volume reduction. The gasification process is an old industrial process that uses heat in an O_2-starved environment to break down carbon based materials into fuel gases. It is closely related to combustion and pyrolysis, but there are important distinctions between them. Gasification is similar to starved-air burning because O_2 is strictly controlled and limited so that the feedstock is not allowed to be completely burned as heat is applied. Instead of combusting, the raw materials go through the progress of pyrolysis, producing char and tar. The char and tar are broken down into syngas, mainly composed of H_2 and CO, as the gasification process continues. The global gasification reaction is written as follows; waste material is described by its ultimate analysis (CH_xO_y) [28]:

$$CH_xO_y + wH_2O + mO_2 + 3.76mN_2 \rightarrow aH_2 + bCO + cCO_2 + dH_2O + eCH_4 + fN_2 + gC \qquad (1)$$

where w is the amount of water per mole of waste material, m is the amount of O_2 per mole of waste, a, b, c, d, e, f and g are the coefficients of the gaseous products and soot (all stoichiometric coefficients in moles). This overall equation has also been used for the calculation of chemical equilibrium occurring in the thermal plasma gasification with input electrical energy [28]. The concentrations of each gas have been decided depending on the amount of injected O_2, H_2O, and input thermal plasma enthalpy. The detailed main reactions are as follows [28, 29]:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \text{ (CH}_4 \text{ decomposition-endothermic)} \qquad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (water gas shift reaction-exthermic)} \qquad (3)$$

$$C + H_2O \rightarrow CO + H_2 \text{ (Heterogeneous water gas shift reaction-endothermic)} \qquad (4)$$

$$C + CO_2 \rightarrow 2CO \text{ (Boudouard equilibrium-endothermic)} \qquad (5)$$

$$2C + O_2 \rightarrow CO \tag{6}$$

The H_2 and CO generated during the gasification process can be a fuel source. Therefore, plasma gasification process has been combined with many other technologies to recover energy from the syngas. Representatives include a combination with the integrated gasification combined cycle (IGCC), fuel cells, and the production of high purity H_2 [26, 30, 31].

Heberlein and Murphy [32] described that a typical plasma system for the treatment of solid wastes consists of (a) the plasma furnace, with a metal and the slag collection at the bottom that periodically tapped and cast into some usable form and power supply, cooling water supplies, gas supplies, and control and data acquisition equipment; (b) a secondary combustion chamber for allowing sufficient residence time at elevated temperatures to assure complete reactions and gasification of soot; this secondary combustion chamber can be fired either by a burner or by a low power non-transferred plasma torch; (c) depending on the waste, a quenching chamber (usually water quencher) to avoid formation of dioxins and furans; (d) a cyclone or bag-house for particulate removal; (e) a scrubber for eliminating acidic gases; (f) if necessary a hydrogen sulfide absorber; (g) high efficiency filters or precipitators for small particulate removal; (h) an activated carbon filter for removal of heavy metals; (i) finally a fan for generating sub-atmospheric pressure in the entire installation. Additionally, various forms of waste preparation and feeding systems have to be integrated with the furnace. Therefore, to operate such a plant, many careful considerations are necessary. Figure 1 shows the necessary technologies boundary. Initially, total process control and safety management systems are necessary. A thermal plasma plant consists of a number of unit processes. To make each process connect with others efficiently, a total control system is essential. In addition, a safety management system is also necessary to protect workers. Based on these two fundamental systems, solid waste pretreatment, plasma torch and furnace, waste heat recovery, power generation, air pollutant control, and syngas utilization systems are necessary.
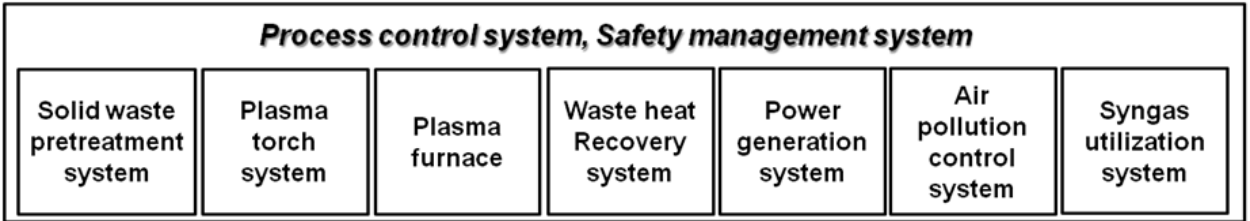
Process control system, Safety management system						
Solid waste pretreatment system	Plasma torch system	Plasma furnace	Waste heat Recovery system	Power generation system	Air pollution control system	Syngas utilization system

Figure 1. Technologies boundary for the thermal plasma gasification plant for solid wastes treatment

The most important part for the mentioned specific systems is the gasification furnace equipped with a thermal plasma generator. Direct current (DC) arc plasma has been mainly used for the treatment of MSW. It has generated through torch-shaped plasma generator. The plasma torch generates and maintains a gaseous electrical conducting element (the plasma) and uses the resistance of the plasma to convert electricity into heat energy. The use of plasma torches is not new. Westinghouse (now a subsidiary of AlterNRG) reportedly began building plasma torches for the National Aeronautics and Space Administration (NASA) in conjunction with the Apollo Space Program as long ago as the 1960s for the

purpose of testing heat shields for spacecraft [33]. In DC arc plasma, the plasma state is maintained between two electrodes of the plasma torch by electrical and mechanical stabilization that are built into the plasma torch hardware. Two arc attachment points are required to generate a plasma column: one attachment point at the solid-gas interface at the cathode electrode and another at the gas-solid interface at the anode electrode [34]. The electrodes are separated by an insulator to preserve the potential difference between them. Very high temperatures are encountered at the attachment points of the plasma that exceed the melting temperature of any electrode material. Therefore, the vaporization of electrode materials at the attachment points is accepted and water cooling is used to minimize the rate of vaporization of electrode materials to increase the lifetime of electrode. Arc plasma torches can be classified as rod type and well type cathodes according to electrode geometry [35]. Thermal plasma torches can be also divided into transferred and non-transferred types depending on whether or not arc attaches onto a substrate directly. Tailored thermal plasma characteristics such as input power level, plasma flame volume, temperature field, velocity distribution, and chemical composition can be achieved for each application.

Generally, the plasma gasification furnace is a type of vertical shaft conventionally used in the foundry industry for the re-melting of scrap iron and steel. Solid wastes have been injected into the top of furnace. The furnace is internally lined with the appropriate refractory to withstand high internal temperatures and the corrosive operating conditions within the furnace. The plasma torches were installed in the bottom of the furnace to enhance the melting of inorganic materials contained in solid wastes. The preliminary size of the standard plasma gasification furnace, for example AlterNRG is 9.7 m outer diameter at its widest point and 19 m overall height [36]. Recently, Solenagroup designed a new furnace concept with a plenum zone (residence time ~ 2 sec) [37], which is a secondary combustion chamber for allowing sufficient residence time at elevated temperatures to assure complete reactions and gasification of soot. Solid wastes are injected into the sides of furnace. In both AlterNRG and Solenagroup's furnaces, coke is added with the solid wastes, which is consumed in the furnace at a much lower rate than the waste material due to its low reactivity, and forms a bed onto which the MSW falls and is quickly gasified. The coke bed also provides voids for molten flux, slag, and metal to flow downward as the gas flows upward. The coke also reacts with the incoming O_2 to provide heat for the gasification of the feed materials. Its role is similar with that of coke in a blast furnace of a steel-making plant.

The components of the other processes for the thermal plasma gasification are shown schematically in Figure 2. To gasify solid wastes, they must be properly treated before adding them into the thermal plasma furnace. The pretreatment process is typically composed of sorting and crushing units like a conventional incineration facility. The pretreated MSW is injected into a gasification furnace equipped with thermal plasma torches. Sometimes, LPG burner is installed to raise the initial temperature and to add heat when the heat value of solid waste is not enough. Coke is also a good assistant heating material as mentioned above. The gas temperature is very high (>1,200 °C) in the thermal plasma furnace, so the temperature of the gas emitted from the thermal plasma furnace

must be decreased. Generally, a heat exchanger is installed behind the thermal plasma furnace to recover the heat from the gas. The recovered heat can also be utilized as an energy source using a steam turbine. The cooled gases passed through the heat exchanger must be purified to generate clean syngas.

There are many options to treat gases containing syngas. Generally, bag filters and wet scrubbers are used to remove fly ash and acidic gases. One advantage in using thermal plasma gasification is that NO_x removal process such as selective non-catalytic reduction and selective catalytic reduction is not necessary because thermal plasma gasification does not emit NO_x since the inside of the plasma furnace is O_2 starved.

After air pollution control the purified syngas (H_2 and CO) can be used as an energy source. First, electricity can be generated by steam and/or gas turbines. For electricity generation by steam turbine, the syngas is just combusted, generating steam which is injected into the steam turbine. The gas turbine can be used for the generation of electricity from the syngas even though additional equipment such as gas purifiers and syngas compressors are necessary. Second, high value chemicals can be produced from the syngas by the combination of chemical processes. CH_4 can be generated with a methanation process, and chemical wax can also be generated using a Fischer-Tropsch process. It also can generate high purity H_2 which can be used as raw material in fuel cells to generate electricity. However, currently, the combination of thermal plasma process with methanation, Fischer-Tropsch, and fuel cell with high purity H_2 processes has not been implemented. We have believed that, if thermal plasma gasification process will combine with them, its applicability will be also widen. As shown in Figure 2, thermal plasma technology for the gasification of solid wastes is comprised of multiple combined element technologies.
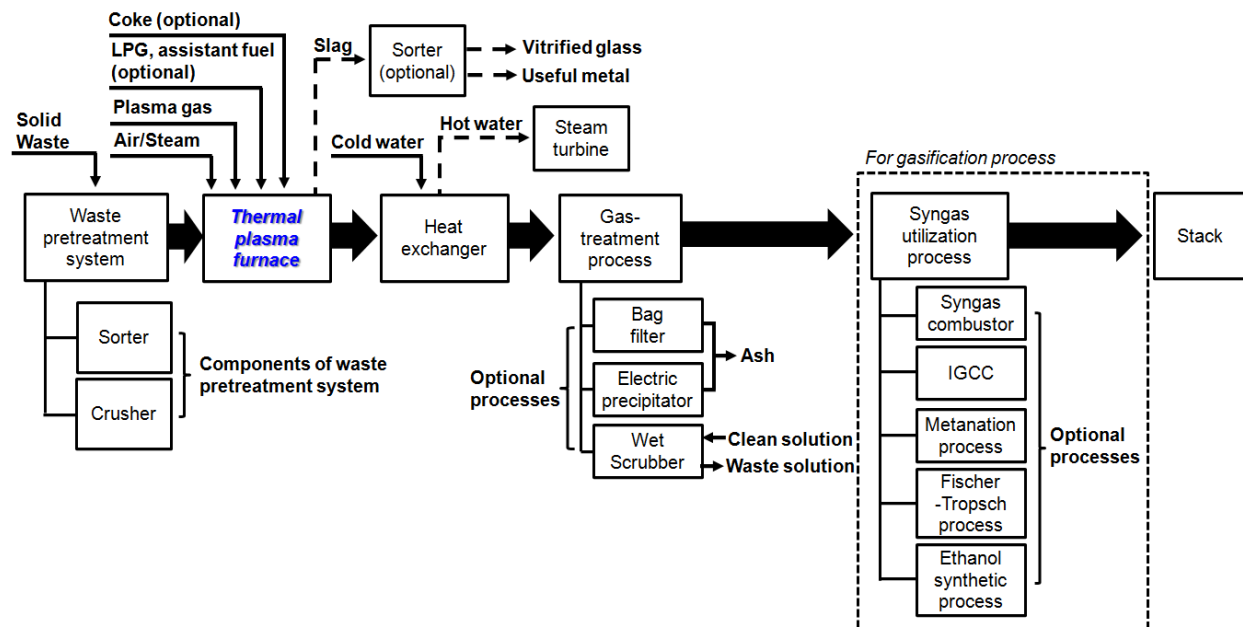

Figure 2. Schematic diagram of the overall process for the gasification of solid waste using thermal plasma

Locations	Population	Materials	Capacity (TPD)	Start date
Europe				
Landskrona, Sweden	27,889	Fly ash	200	1983
Bordeaux, France	1.01 million	Ash from MSW	10	1998
Morcenx, France	4,993	Asbestos	22	2001
Bergen, Norway	213,000	Tannery waste	15	2001
North America				
Anniston, Albama	24,276	Catalytic converters	24	1985
Jonquiere, Canada	54,872	Aluminum dross	50	1991
Honolulu, Hawaii	374,676	Medical waste	1	2001
Richland, Weshington	46,155	Hazardous waste	4	2002
Alpoca, West Virginia	613	Ammunition	10	2003
USA Navy	-	Shipboard waste	7	2004
USA Army	-	Chemical agents	10	2004
Hawwthorne, Nevada	3,311	Munitions	10	2006
Ottawa, Canada	1.1 million	MSW	85	2007
Madison, Pennsylvania	510	Biomass, Const. waste	18	2009
Asia				
Kinura, Japan	40,806	MSW Ash	50	1995
Mihama-Mikata, Japan	28,817	MSW/Sewage sludge	28	2002
Utashinai, Japan	5,221	MSW/ASR	300	2002
Shimonoseki, Japan	1.5 million	MSW Ash	41	2002
Imizu, Japan	94,313	MSW Ash	12	2002
Kakogawa, Japan	268,565	MSW Ash	31	2003
Maizuru, Japan	89,626	MSW Ash	6	2003
Lizuka, Japan	78,201	Industrial waste	10	2004
Taipei, Taiwan	22.2 million	Medical and battery waste	4	2005
Osaka, Japan	2.6 million	PCBs (Poly chlorinated Biphenyl)	4	2006
Cheongsong, Korea	150,000	MSW	10	2008

Table 1. Commercial thermal plasma plants of solid waste treatment [39]

There are a number of applications of commercial thermal plasma facilities for various solid wastes treatment in the EU, the USA, and Asia (Table 1). Especially, Japan and the EU have constructed many thermal plasma processing plants; the largest of which is located in Utashinai, Japan has a 300 TPD capacity for the treatment of MSW and ASR (auto shredder residue). Several major companies manufacture thermal plasma torches (Westinghouse, Europlasma, Phoenix, and Tetronics). Westinghouse has supplied a maximum 2.4 MW thermal plasma torch having an approximately 1,500 hr lifetime [38]. Europlasma has

Supplier	Nation	Materials
AlterNRG	Canada	MSW, RDF (refuse derived fuel), ASR, tire, coal and wood, hazardous waste, petcoke
Advanced Plasma Power (APP)	UK	RDF
Bellwether Gasification Technologies	Germany	MSW, RDF
Bio Arc	USA	Agricultural waste, medical waste
Blue Vista Technologies	Canada	MSW, hazardous liquids and gaseous wastes
Environmental Energy Resources (EER)	Israel	MSW
Encore Environmental Solutions	USA	Hazardous waste
Enersol Technologies	USA	LLR (low level radioactive), munitions
Enviroarc Technologies	Norway	Tannery waste, other hazardous waste, ash
Europlasma	France	Hazardous waste, ash, MSW, tires, syngas cleaning
GS Platech	Korea	MSW, biomass, ASR, industrial waste, hazardous waste, sludge, radioactive waste
Hera Plasco	Spain	MSW
Hitachi Metals	Japan	MSW and ASR, MSW and sewage sludge
Hitachi Zosen	Japan	Ash
Hungaroplazma Services	Hungary	MSW
InEnTec	USA	Medical waste, hazardous waste
International Scientific Center of Thermophysics and Energetics (ISCTE)	Russia	Transformer oil, pesticide, medical wastes, waste oil and coal slimes
Kawasaki Heavy Industries	Japan	PCBs and asbestos
Kinectrics	Canada	MSW, waste plastics
Mitsubishi Heavy Industries	Japan	Ash
MPM Technologies	USA	ASR, sewage sludge, waste tires and petcoke, biomass
MSE Technology Applications	USA	Military, hazardous waste
Plasma Energy Applied Technology (PEAT) International	USA	Hazardous waste, medical, industrial process and pharmacy waste
Phoenix Solutions	USA	Ash
Plasco Energy	Canada	MSW
Pyrogenesis	Canada	Shipboard waste, industrial waste

| Supplier	Nation	Materials
Radon	Russia	LLR and hazardous waste
Retech Systems	USA	Hazardous wastes, LLR wastes
SRL Plasma	Australia	Solvent, waste chemicals and CFC's (chloro fluoro carbon)
Startech Environmental	USA	MSW
Tetronics	UK	Ash, APC residues and hazardous waste, catalyst waste, steel plant wastes, hazardous waste, RDF

Table 2. Suppliers and treated materials for the treatment of solid wastes in the world [43]

developed a maximum 4.0 MW transferred torch, also with 1,500 hr lifetimes [40]. Phoenix has developed transferred, non-transferred, and convertible thermal plasma torches with a maximum power of 3 MW and lifetimes of about 2,300 hr [41]. Tetronics has developed transferred, non-transferred, and twin torches having approximately 1,000 hr lifetimes [42]. In addition, many suppliers have also widely distributed (especially North America and EU) for various material treatments using thermal plasma (Table 2) [43]. These findings lead us to believe that thermal plasma technology for the treatment of solid waste is well-established technology and is immediately usable for solving problems for waste treatment.

3. Characteristics of thermal plasma process for the gasification of MSW

Combustion can play a number of important roles in an integrated MSW management system as follows: it can (1) reduce the volume of waste, therefore preserving landfill space, (2) allow for the recovery of energy from the MSW, (3) permit the recovery of minerals from the solid waste which can then be reused or recycled, (4) destroy a number of contaminants that may be present in the waste stream, and (5) reduce the need for the "long-hauling" of waste.

The recovery of energy from MSW combustion typically involves the conversion of solid waste to energy resulting in the generation of electricity from the recovered heat, and/or the generation of hot water or steam to use for community-based industrial, commercial or residential heating applications. Conventional combustion technologies include mass burn incineration. On the basis of chemical analysis, the average composition of combustible materials in MSW can be expressed by the formula $C_6H_{10}O_4$ [44]. When this hypothetical compound is combusted with air, the reaction is [44]:

$$C_6H_{10}O_4 + 6.5O_2 + (24.5N_2) \rightarrow 6CO_2 + 5H_2O + (24.5N_2) \qquad \Delta H = -6.5 \text{ MWh /ton} \qquad (7)$$
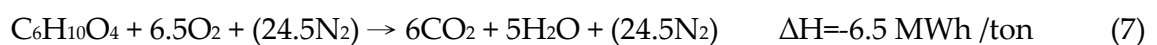
Although, incineration technology has been widely utilized to reduce the total volume of waste and recover the energy from MSW, the emissions of pollutants such as NO_x, SO_x, HCl, harmful organic compounds, and heavy metals are high. Another problem is the serious corrosion of the incineration system by alkali metals contained in solid residues and fly ash

[45]. Thermal plasma technology has been applied for the treatment of MSW as an alternative to solve these problems [46-48].

Thermal plasma technology can make extremely high temperatures in the absence of or near-absence of O_2, with MSW containing organics and other materials. Organics are converted into syngas and other materials dissociated into constituent chemical elements that are then collected and vitrified to produce an inert glass-like slag; most of the heavy and alkali metals (with the exception of mercury, zinc and lead, which can vaporize at high temperatures and be retained in fly ash and syngas) are retained in the vitrified slag. The vitrified slag obtained after cooling can be used as construction materials. The simple gasification reaction of MSW using thermal plasma can be expressed as follows [44]:

$$C_6H_{10}O_4 + 3O_2 \rightarrow 3CO + 3CO_2 + 4H_2 + H_2O \qquad \Delta H=\text{-1.3 MWh/ton} \qquad (8)$$

The principal product of plasma gasification of MSW is a low to medium calorific value syngas composed of CO and H_2 as shown in equation (8). This gas can be burned to produce heat and steam, or chemically scrubbed and filtered to remove impurities before conversion to various liquid fuels or industrial chemicals. Syngas combusts according to the following equations [44]:

$$3CO + 4H_2 + 3.5O_2 \rightarrow 3CO_2 + 4H_2O \qquad \Delta H=\text{-1.5 MWh/ton} \qquad (9)$$

Occasionally, steam has been injected with MSW into plasma gasification furnaces to increase the energy efficiency and syngas yield according to equations (1)-(4). Nishikawa et al. reported that steam enhanced the reduction of the weight of charcoal and production of hydrogen through laboratory experiments [49]. Qinglin et al. also investigated the effect of steam injection in pilot scale thermal plasma gasification plant of MSW [45], showing that the cold gas efficiency and syngas yield are improved with the increase of steam injected.

Table 3 shows the important differences mentioned above between incineration and thermal plasma gasification. Main differential factors between them are amount of added O_2 and temperature inside a furnace. Incinerators have designed to maximize CO_2 and H_2O, indicating complete combustion, however thermal plasma treatment system is designed to maximize CO and H_2, indicating incomplete combustion. These complete and incomplete combustions have been controlled using added O_2 amounts. Incinerators add a large quantity of excess air, but thermal plasma treatment systems add a limited quantity of O_2. Therefore, inside of incineration furnace is an oxidizing environment, causing the generation of NO_x and SO_x, but inside of thermal plasma process is a reducing environment, prohibiting the generation of NO_x and SO_x. Temperature of incineration furnaces is around 800 °C which is below an ash melting point. This makes inorganic materials contained in MSW to convert to bottom and fly ash. However, temperature of thermal plasma processes is around 1,400 °C, which is above an ash melting point. This makes inorganic materials contained in MSW to convert to vitrified slag which can be utilized as a source of construction materials.

Differential factors	Incineration process	Thermal plasma process
Definition	- Mass burning process	Gasification process
Amount of O_2	- Designed to maximize CO_2 and H_2O - Added large quantity of excess air - Oxidizing environment - Generating NO_x and SO_x	- Designed to maximize CO and H_2 - Added limited quantity of O_2 - Reducing environment - Prohibiting the generation of NO_x and SO_x
Temperature	- Operating at temperature below ash melting point - Inorganic materials are converted to bottom ash and fly ash - Bottom ash and fly ash are collected, treated, and disposed as hazardous wastes.	- Operating at temperature above ash melting point - Inorganic materials are converted to glassy slag and fine particulate matter - Slag is non-leachable, non-hazardous and suitable for use in construction materials

Table 3. Comparison between the incineration and thermal plasma gasification processes for MSW treatment

4. Operation status of 10 TPD scale thermal plasma gasification plant for MSW treatment

A 10 TPD capacity thermal plasma plant for MSW treatment is located in Cheongsong, Korea. The local population of 30,000 generates 15 TPD MSW. The characteristics of the MSW are shown in Table 4 [27]. The thermal plasma plant was constructed in early 2008 and optimized for 6 months beginning in September, 2008. The plant continues to operate normally for over 3.5 years without any problems.

During the optimization period, several attempts were made to improve the performance of the process for normal waste feeding system, control of the hot air flow rate added into the furnace, removal of bag-filter and other considerations were made. Operating data of the thermal plasma gasification plant have been obtained during the normal operation periods (3.5 years). An exterior image and interior 3D design scheme of the thermal plasma plant are shown in Figures 3 and 4, respectively. The thermal plasma gasification plant mainly consists of a waste feeding system, integrated thermal plasma furnace, heat exchanger, bag filter, water quencher and scrubber, and secondary combustion chamber. Currently we are not using bag filter because we reduced the generated fly ash by employing a centrifugal force using flow jet of the thermal plasma torch inside the furnace, which melted the fly ash and unburned MSW onto the wall of the integrated furnace.

Items		Values
Heating value (kcal/kg)	Higher heating value	4491.09
	Lower heating value	2999.90
Proximate analysis (wt%)	Moisture	24.83
	Combustible	67.54
	Non-combustible	7.64
Ultimate analysis (Dry basis, wt%)	C	45.21
	H	6.37
	N	0.87
	S	0.18
	Cl	0.88

Table 4. Heating values and chemical composition of MSW gathered in Cheongsong, Korea [27]

Figure 3. Exterior image of 10 TPD thermal plasma gasification plant located in Cheongsong, Korea

Detailed specifications of 10 TPD thermal plasma gasification plant can be found in reference [27]; in this chapter, we summarize specifications and performances compactly. The integrated furnace, equipped with two non-transferred thermal plasma torches, is the central apparatus where the gasification takes place. The operating pressure of the

integrated furnace is maintained at -10 mmAq gauge pressure (Figure 5(a)); the increase of pressure after November was caused by the modification of operation conditions for the combination of thermal plasma process with fuel cells. The integrated furnace is composed of the furnace, two non-transferred thermal plasma torches, a preheating burner that uses liquefied petroleum gas (LPG), a MSW feeding system, an outlet for the melted slag, and a hot air injection port. The role of the preheating burner is to preheat the integrated furnace (up to 600 °C for the initial 12 hr). The temperatures inside the integrated furnace and syngas combustor are maintained at 1,400 and 880 °C, respectively (Figure 5(b)). The MSW is initially partially oxidized by the injection of hot air (600 °C, 700 Nm^3/hr), which is taken from the air preheater/gas cooler, and then melted by the plasma torches. This partial oxidation of MSW can reduce the electrical energy used for the thermal plasma torches. The melted slag is tapped out into a water tank from a hole located at the bottom of the furnace. This molten slag is quenched with water to produce granulated slag, which is removed using the slag conveyer belt. Two non-transferred thermal plasma torches are installed into the integrated furnace (Figure 6) at a 30° angle to induce a centrifugal force in the furnace. An image of the thermal torches and an interior view of the plasma torch are shown in Figure 7. The power capacity of each plasma torch is 200 kW, with an operational voltage and current of 571 ± 30 V and 293 ± 10 A, respectively (Figure 5(c)). The efficiency of the plasma torches is approximately 70% and the lifetime of the electrode is about 500 hr. Air (500 L/min, at 490 kPa) is supplied to the thermal plasma torches using a compressor.
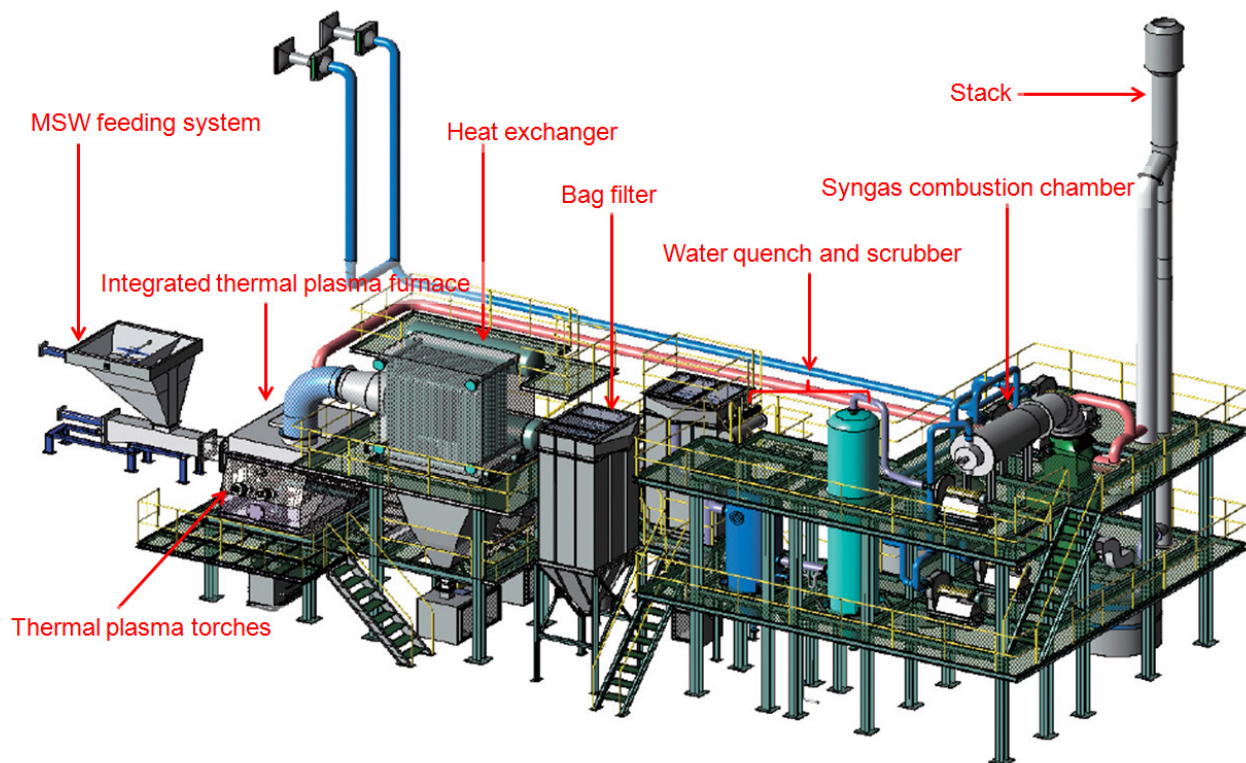

Figure 4. Interior 3D scheme of 10 TPD thermal plasma gasification plant located in Cheongsong, Korea
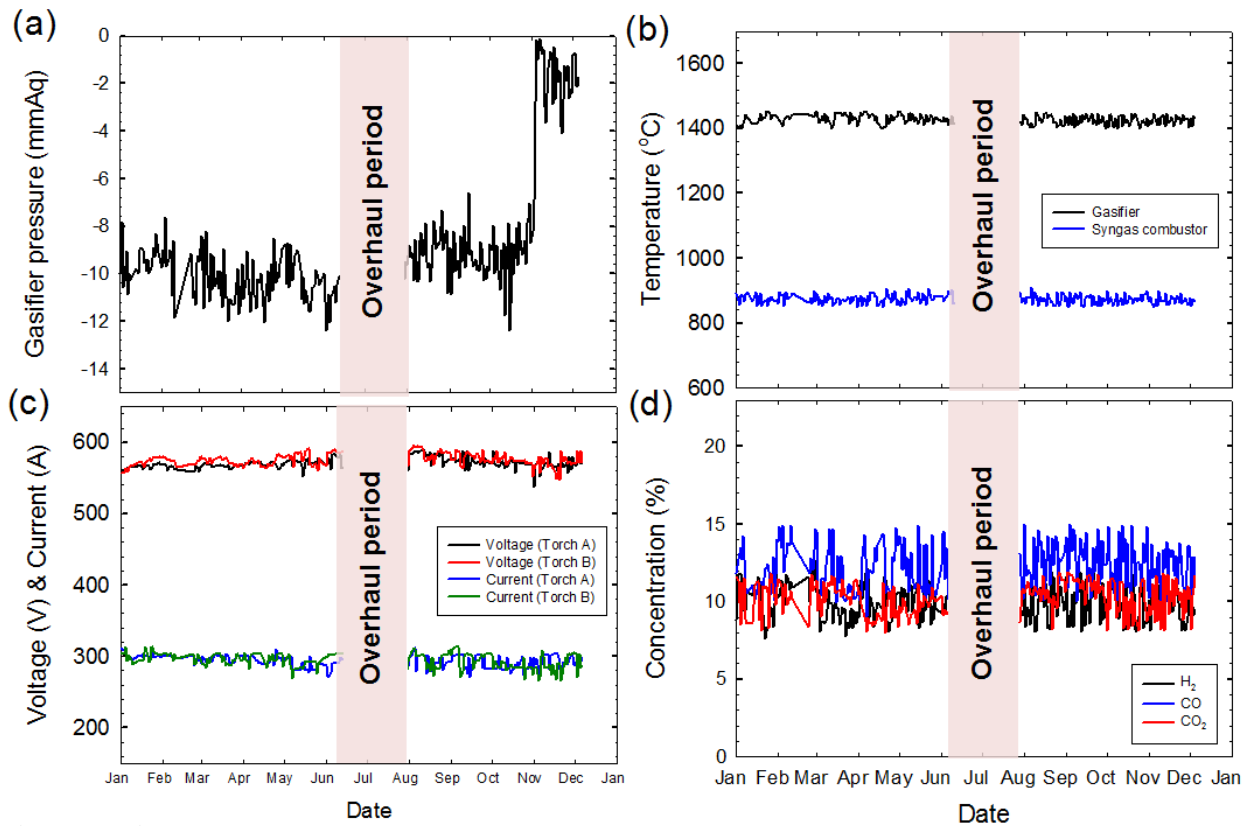
Figure 5. Measured characteristics of thermal plasma gasification plant for 1 year. (a) Pressure inside the integrated thermal plasma furnace and syngas combustion chamber. (b) Temperature inside the integrated thermal plasma furnace. (c) Applied voltage and current at two thermal plasma torches. (d) H_2, CO, and CO_2 concentration of integrated thermal plasma furnace

The gas produced in the integrated furnace (1,400 °C) enters the steam generator, where the temperature is cooled to 180 °C. Steam is generated at 1.2 ton/hr, and then injected into the steam condenser and recirculated to the steam generator. The gas cleaning systems eliminate acidic gases prior to the gas entering syngas combustion chamber. For this purpose water quencher and scrubber are installed in series. The water quencher and scrubber are located at the outlet of the heat exchanger. The role of the water quencher is to cool the gas to 30 °C with NaOH solution (40%). Although the remaining acidic gases are also partially removed by the water quencher, almost all acidic gases are removed in the scrubber. The scrubbing solution is controlled at pH 9.0, and recirculated. A syngas combustion chamber is installed to combust the H_2 and CO gases emitted. Air taken out from the MSW storage is added to the chamber to completely combust the H_2 and CO with an LPG burner, which utilizes 4.76 Nm^3/ton of LPG. The temperature of the syngas combustion chamber is maintained close to 900 °C (Figure 5(b)).

The purpose of the air preheater and gas cooler is to increase the temperature of the air taken from the MSW storage to 600 °C, and decrease the temperature of the gas emitted from the syngas combustion chamber to 200 °C. The heated air is injected into the integrated furnace to partially oxidize the MSW (700 Nm^3/hr).
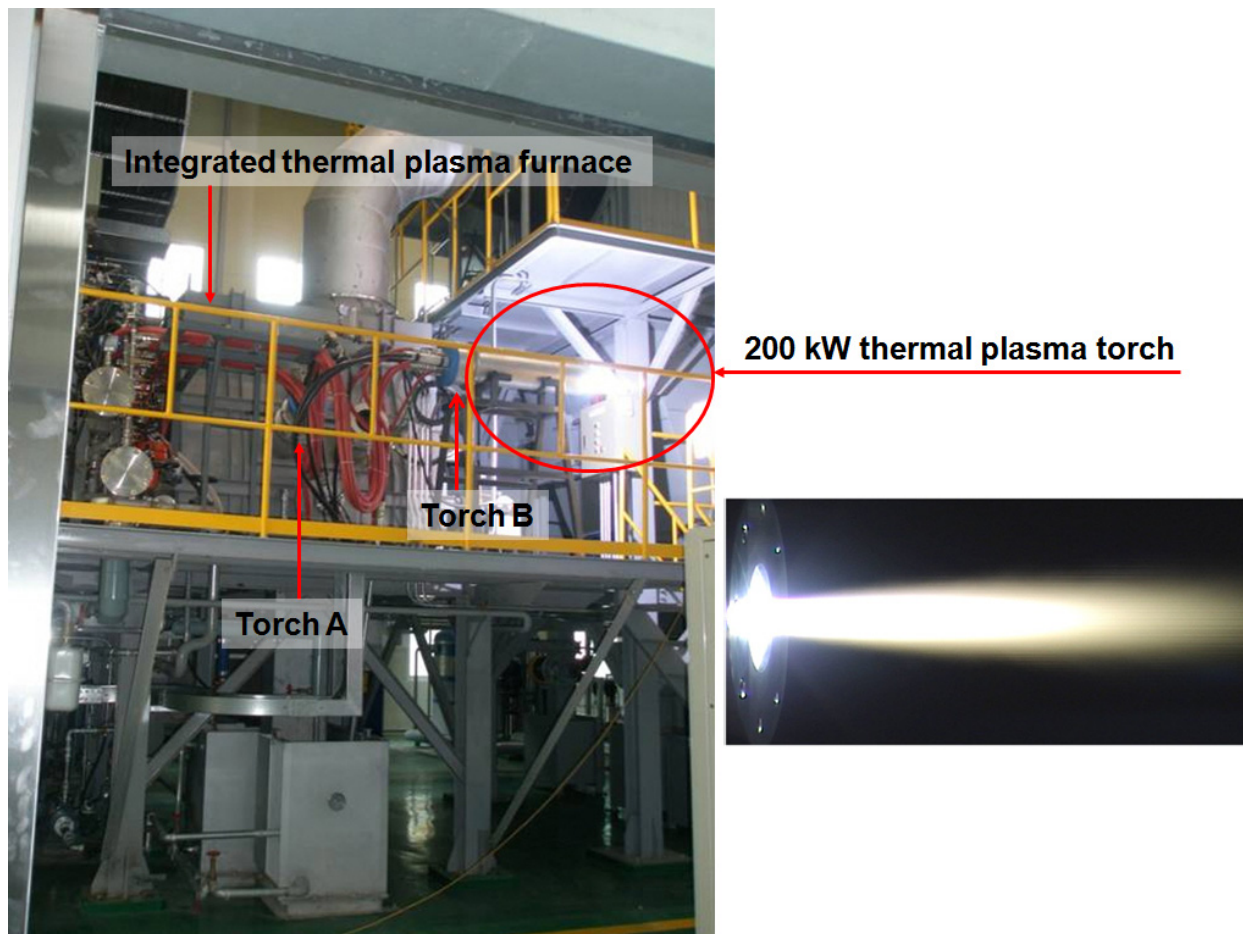
Figure 6. Image (left) of the generated thermal plasma using 200 kW thermal plasma torch beside the integrated furnace. Detailed image of the generated thermal plasma (right)
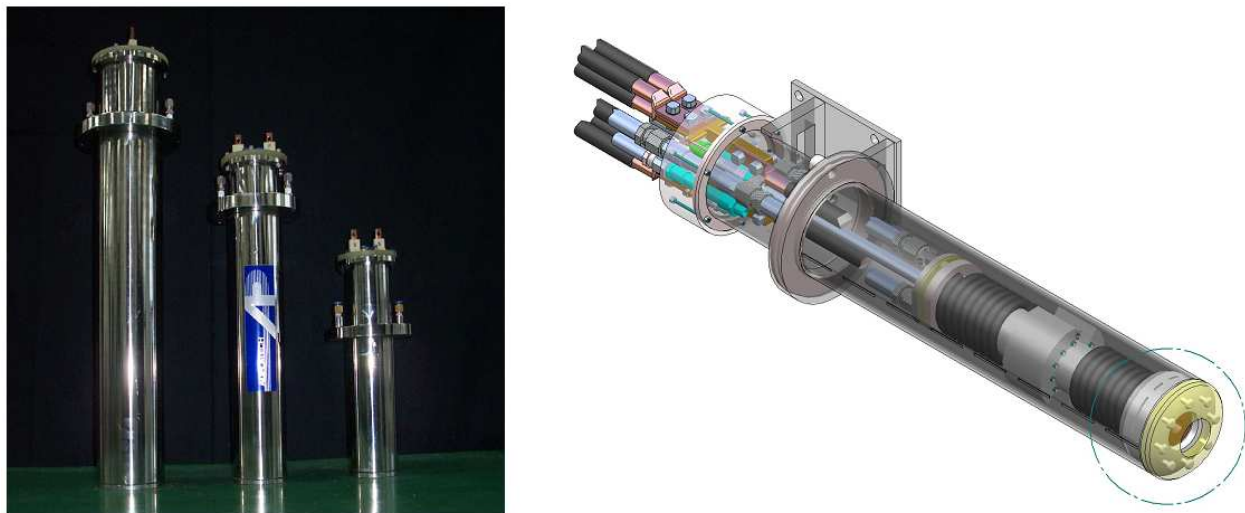

Figure 7. Images of thermal plasma torches manufactured from GS Platech (left) and interior view of thermal plasma torch (right) installed at the integrated furnace

Solid, liquid, and gaseous byproducts are generated from the thermal plasma gasification plant. Solid byproducts originate from the integrated furnace as slag (75.8 kg/ton (7.8% to

the inlet MSW)) (Figure 8), the liquid byproducts are from the wastewater treatment system (0.43 Nm³/ton), and the gaseous byproducts are from the gasification of MSW and the combustion of syngas.

The composition of the slag was analyzed and shown to have SiO_2, Al_2O_3, CaO, Fe_2O_3, Na_2O, and MgO as the major constituents, with a total percentage of 97%. The weight percentage of the inlet MSW that becomes slag is 7.58%. In addition, the rate of MSW volume reduction to slag was up to 99% (the density of MSW: 0.09 ton/m³, slag: 2.6 ton/m³). This result indicates that the treatment of MSW using thermal plasma processes can greatly reduce the volume of MSW. A toxicity characteristics leaching procedure was performed on three slag samples. No heavy metals were eluted from the slag (Table 5). This result indicated that the slag produced in the thermal plasma process from the treatment of MSW is non toxic.
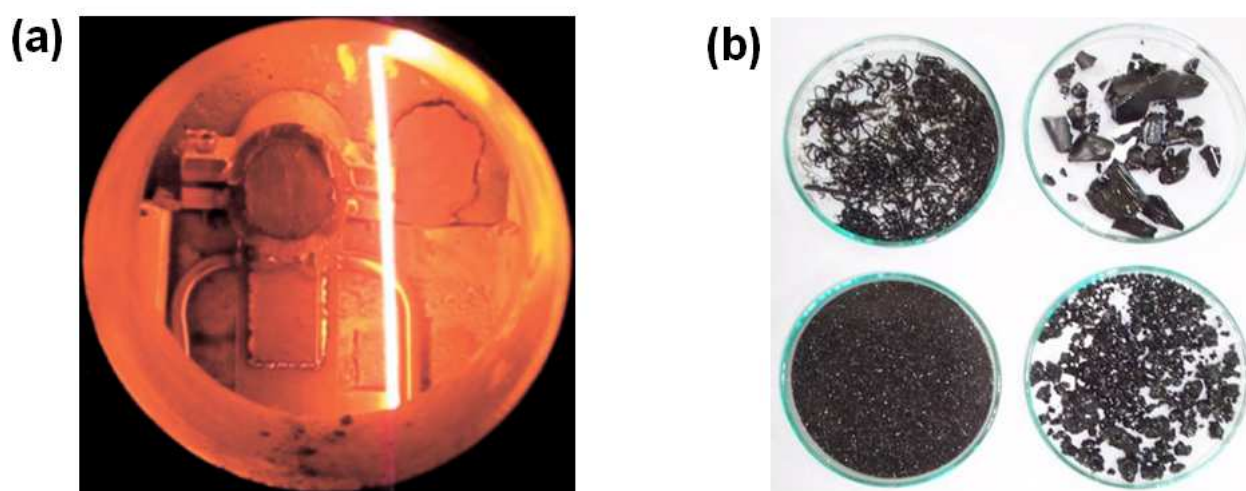

Figure 8. Images of (a) molten slag tapped from integrated furnace and (b) vitrified slag

Measurement times	Pb (mg/L)	Cd (mg/L)	As (mg/L)	Cu (mg/L)	Hg (mg/L)	Cr⁶⁺ (mg/L)
1	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
4	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
5	N.D.	N.D.	N.D.	0.05	N.D.	N.D.
Average	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

N.D.: not detected

Table 5. Results of toxicity characteristics leaching procedure for vitrified slag

The discharged liquid originating from the water quenching and scrubbing, which was used to decrease the gas temperature and remove the acidic gas, amounted to 0.43 Nm³/ton. This

wastewater was treated via the wastewater treatment system and recycled into the water quencher and scrubber.

The most crucial point in the operation of a thermal plasma process is the nature and amount of the final air emissions. The concentrations of air pollutants were measured at two ports: one at the outlet of the integrated furnace, and the other at the stack. We also measured the concentration of gaseous emission at two ports for 1 year (Figure 5(d) and Table 6); we measured syngas continuously at the outlet of the integrated furnace (Figure 5(d)) and air pollutants periodically at the stack (Table 6). The flow rates at the outlet of the integrated furnace and stack were 1,161 and 2,654 Nm^3/hr, respectively. The higher flow rate at the stack was due to the syngas combustion chamber that used air and LPG. The concentrations of O_2 at the outlet of the integrated furnace and scrubber were 0.4 ± 0.2 and 1.1 ± 0.4%, respectively. The small concentration of O_2 in the integrated furnace indicates that the inside was under O_2 starved conditions. The average concentrations measured at the outlet of the integrated furnace were 10.4% for H_2 and 14.2% for CO with 10% CO_2 (Figure 5(d)); extra gases are mostly N_2. The fluctuation of concentrations was caused by the variation of waste composition and water content. The syngas combustion chamber was employed for the combustion of H_2 and CO at the present 10 TPD scale without the reuse of the syngas. It is worth noting that no NO_x and SO_x were detected at the outlet of the integrated furnace due to the O_2-starved conditions inside the integrated furnace. The concentrations of dioxin were 1.04 ng-TEQ/Nm^3 at the outlet of the integrated furnace and 0.05 ng-TEQ/Nm^3 at the stack, which were much lower than those of conventional incineration plants. This result suggests that negligible amounts of PCDD/DFs were produced in the thermal plasma gasification plant due to the high temperature of the integrated furnace. The concentrations of NO_x and SO_x were 10 and 4 ppm, respectively, which is increased somewhat at the stack. This is because of the syngas combustion chamber. The concentrations of CO, HCl, and dust are 5 ppm, 1.92 ppm, and 4.15 mg/Sm^3, respectively, which satisfied the requirements of current legislation. These results indicated that the thermal plasma process for the treatment of MSW is an environmentally friendly process.

As mentioned above, we don't reuse the generated syngas for the recovery of energy at 10 TPD thermal plasma gasification plant; we have just combusted syngas in the syngas combustion chamber. However, recently, we have tried to utilize syngas generated from MSW as an energy source. We combined the thermal plasma gasification plant with 50 kW proton exchange membrane fuel cell (PEMFC) from November, 2010 to October, 2011. We installed WGS and PSA to make high purity H_2 (> 99.999%); we already demonstrated to make high-purity H_2 (>99.99%) using WGS and PSA in 3 TPD thermal plasma gasification plant using paper mill waste [26]. Finally, we succeed to make high-purity H_2 (>99.999%) and generate electricity from 50 kW PEMFC. We will report those results in time. We have believed strongly that these trials also can widen the applicability of thermal plasma process for MSW.

Date	CO (ppm)	HCl (ppm)	Dust (mg/Sm³)	NOₓ (ppm)	SOₓ (ppm)
14/01/2010	2	1.29	3.7	5	3
29/01/2010	2	2.03	3.4	10	3
12/02/2010	7	1.67	3.5	13	7
03/03/2010	4	1.2	4.1	8	5
12/03/2010	3	2.09	3.9	11	6
26/03/2010	5	1.11	5.2	22	3
16/04/2010	4	1.19	3.4	8	5
30/04/2010	2	3.01	4.7	7	7
15/05/2010	6	1.74	4.9	8	5
28/05/2010	3	2.40	4.2	9	3
14/06/2010	5	1.78	4.0	8	3
04/08/2010	2	1.56	4.40	8	3
13/08/2010	6	2.64	5.20	8	7
27/08/2010	9	2.13	4.60	19	4
10/09/2010	10	1.79	4.20	6	4
02/10/2010	1	2.75	3.90	6	3
08/10/2010	2	2.62	2.50	5	3
22/10/2010	9	2.08	3.80	13	4
05/11/2010	5	1.62	4.60	16	3
19/11/2010	2	2.23	3.60	16	3
14/12/2010	6	1.43	5.40	13	5
Average	5	1.92	4.15	10	4

Table 6. Gas composition measured at the stack of the thermal plasma gasification plant for 1 year

5. Design parameters for a 100 TPD scale thermal plasma gasification plant

Based on the obtained data from the 10 TPD thermal plasma plant, we could obtain design parameters for a 100 TPD plant. It is considered that the MSW has 3,300 kcal/kg of heating value. Figure 9 shows the schematic of overall process of 100 TPD thermal plasma plant for MSW treatment. A 100 TPD thermal plasma plant consists of six main sections for the gasification of MSW: (1) An MSW storage unit and feeding system, (2) an integrated furnace equipped with two non-transferred thermal plasma torches, (3) effluent gas treatment systems, including water quencher and scrubber, (4) a syngas combustion chamber, (5) an air preheater/gas cooler, and (6) a steam turbine (which was not included in the 10 TPD plant). An energy balance for the overall process is presented in Figure 10. The third line of the table inserted in Figure 10 shows the latent heat of the produced syngas. The specific different characteristics between the 10 and 100 TPD scales are also tabulated in Table 7. At 10 TPD capacity, the power consumption of the plasma torch used for the treatment of 1 ton of MSW was 0.817 MWh/ton. At 100 TPD, use of 0.447 MWh/ton of

thermal plasma power is planned. At 10 TPD, the heat loss of the overall process through the wall was 14% and the energy contained in the effluent gases of the stack was 16%. However, we considered, at 100 TPD, the heat loss of the overall process through the wall would be 7% and the energy contained in the effluent gases of the stack would be 10%. In addition, at a 10 TPD scale, syngas and the heat generated from heat exchanger have not been reused, however, at 100 TPD, the energy generated from syngas and heat exchanger through steam generators would be used. The energy reused by the two steam generators would be 73% of the input energy (a ratio of 12 plus 13 (16,679 Mcal/hr) to 1 plus 2 (22,858 Mcal/hr) in Figure 10).

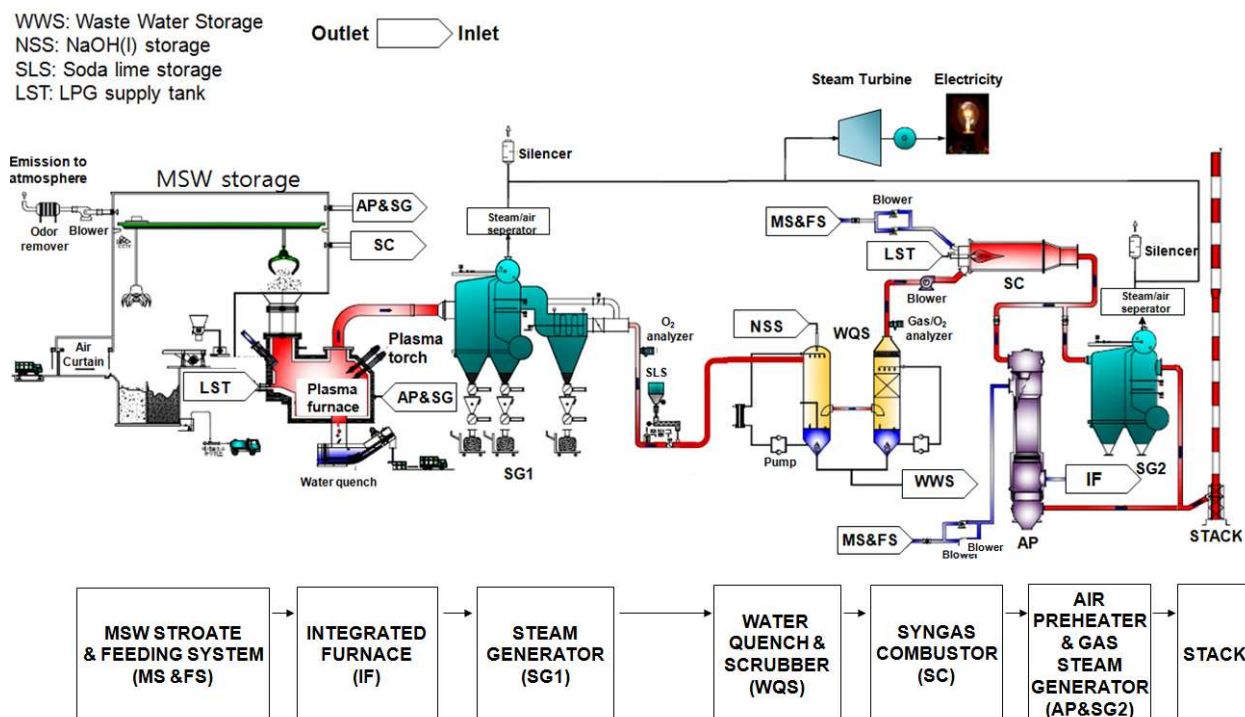| Items	10 TPD scale	100 TPD scale
Thermal plasma consumption power	0.817 MWh/ton	0.447 MWh/ton
Heat loss from effluent gases of stack	16%	10%
Heat loss through system walls	14%	7%
Energy recovery	Not used	Used through steam turbine

Table 7. Comparison of the characteristics between 10 and 100 TPD thermal plasma plants for MSW treatment

Figure 9. Schematic of the overall process for 100 TPD thermal plasma gasification plant

NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
				Sensible Heat	Sensible Heat	Sensible heat								
UNIT							Mcal/hr							
Value	21,740	1,118	251	8,182	937	198	14,967	3,919	178	81	1,695	7,245	9,434	19.2
Latent heat				15,341	15,341	15,341								
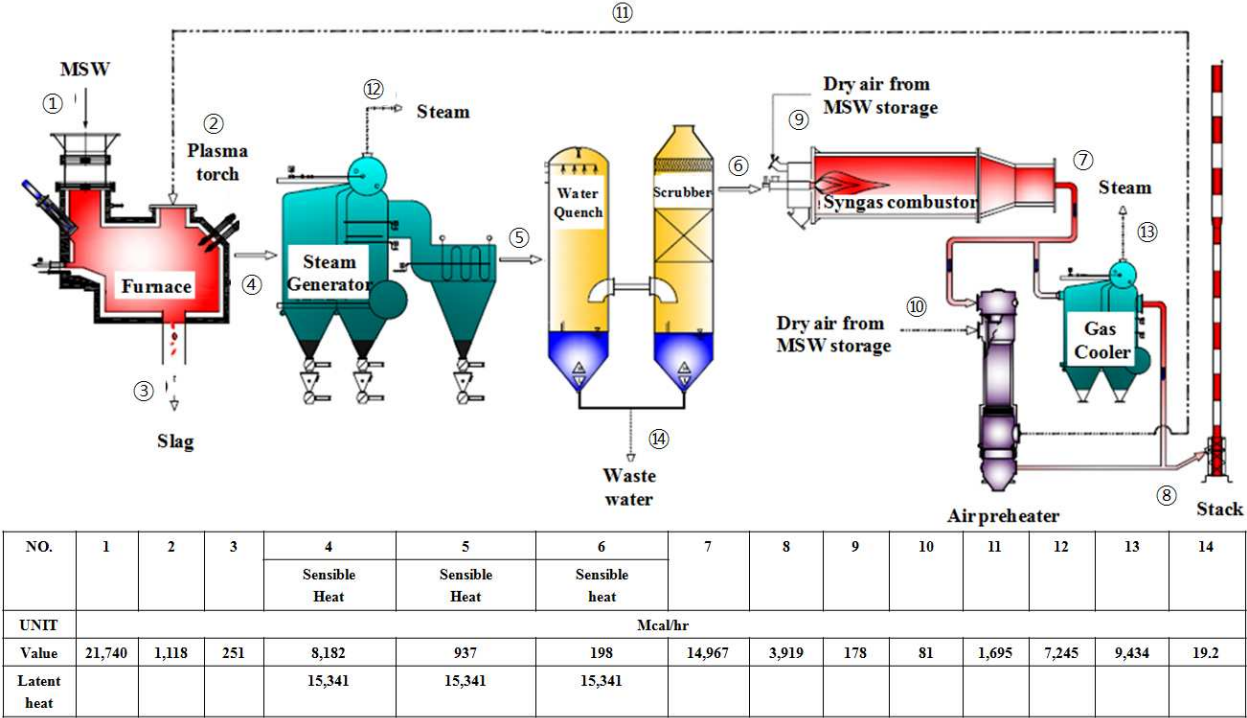
Figure 10. Energy balance for 100 TPD thermal plasma gasification plant

6. Economic evaluation of the thermal plasma gasification plant

The major disadvantage of thermal plasma gasification processes mentioned by many scientists and engineers is the use of electricity, which is an expensive energy source [32]. The economics of thermal plasma gasification processes have many variable parameters such as regional characteristics, types of solid wastes to be processed, capacity, and others. In the USA, the cost of a landfill is approximately 30-80 US$/ton and the average incineration cost is 69 US$/ton [50]. However, the average cost of landfills and incinerators in small countries such as Japan and European countries is approximately 200-300 US$/ton since land is more scarce [50], meaning that the economics of thermal plasma gasification for MSW is improved in these regions. Presently, the average construction cost of thermal plasma plants is estimated to approximately 0.13-0.39 million US$/TPD. Dodge estimated that the construction cost of a 750 TPD is 150 million US$, which is equivalent to 0.2 million US$/TPD [51]. The construction cost of the 300 TPD plant in Utashinai, Japan was approximately 0.17 million US$/TPD. A 600 TPD thermal plasma plant in St. Lucie, Canada planned by Geoplasma using Alter NRG's thermal plasma torch is also 0.17 million US$/TPD. The initial project planning to construct a 2,700 TPD by Geoplasma in St. Lucie had a 0.13 million US$/TPD construction cost. Figure 11 shows the trend of construction cost according to capacity; cases of GS Platech (10 and 100 TPD scales) will be discussed detailed in below. Although the prices of each country are different and data are not enough fully, the trend of construction cost according to capacity could be identified. 0.39 million US$/TPD applies to the 10 TPD plant constructed by GS Platech in Korea. For capacities between 250 and 750 TPD, around 0.17-0.22 million US$/TPD is applicable. Above 2,000

TPD, 0.13 million US$/TPD is applicable. These results indicate that thermal plasma gasification processes are more economical if the treatment capacity is increased. Presently, detailed operational costs of each case are not available other than GS Platech. In addition, there are many methods to utilize byproducts generated during MSW gasification. For example, syngas, which could be used for the generation of high value products such as fuel, chemical compounds, and high purity hydrogen, would work to this effect. This means that, although thermal plasma technology is well-established, there are still many fields to investigate for enhancing the economics of the process.
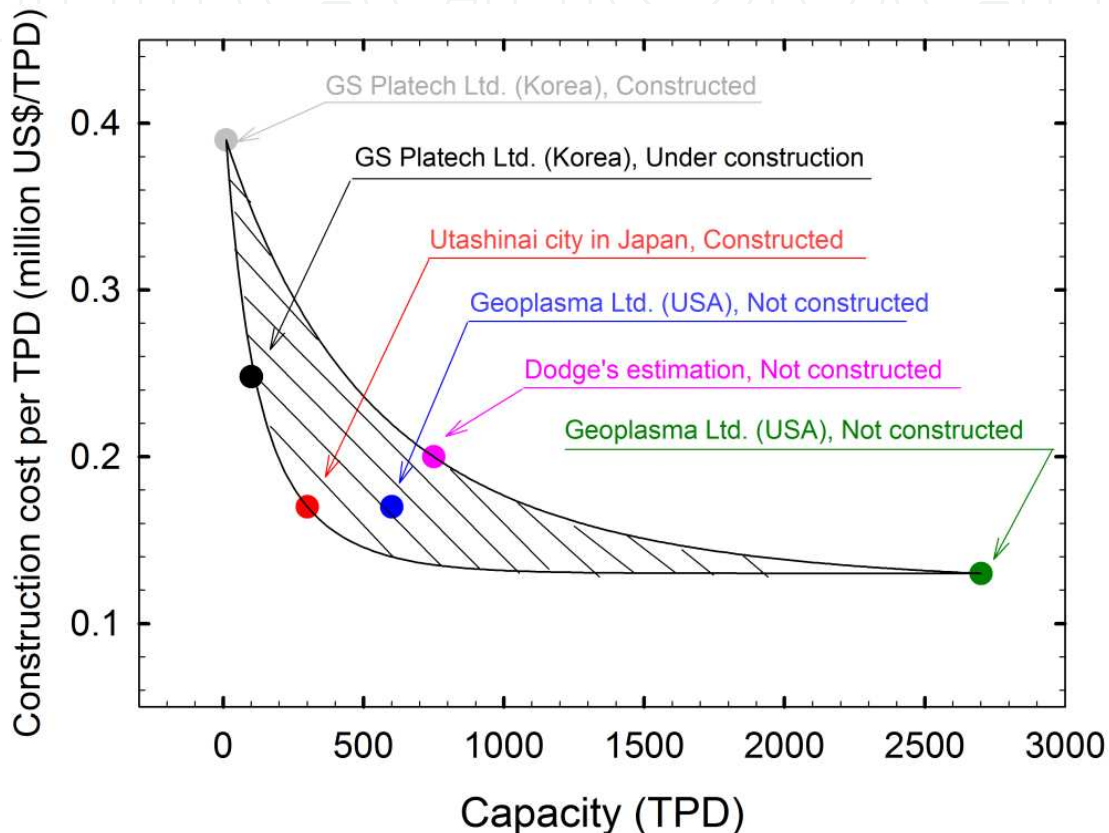

Figure 11. Construction cost (million US$) of thermal plasma treatment plants according to treatment capacity (TPD)

We can obtain detailed economic evaluations for a 10 TPD plant, including construction and operation costs (Table 8). 3.9 million US$ was the total construction cost of a 10 TPD or 0.39 million US$/TPD. Operation costs include labor costs, depreciation cost, overhead charges, and insurance. Labor cost for 12 labors and overhead charges are 0.49 and 0.24 million US$/year, respectively. Depreciation cost and insurance are 0.26 and 0.02 million US$/year, respectively. Total operation costs are 0.99 million US$/year. This is equivalent to 300 US$/ton without VAT. 110 US$/ton is received from local government for treating MSW in Cheongsong, Korea, which would vary by region. Therefore, total profit is negative (-190 US$/ton). However, economics will be improved if treatment scale is increased because of the following three reasons. First, the construction cost will be decreased as the capacity is increased, as mentioned above. This will cause a decrease in depreciation cost. Second,

syngas can generate profit as an energy source. Presently, we are abandoning generated syngas because the amounts generated are not sufficient to use as an energy source. Lastly, the operation of a plant is an economy of scale. As the capacity increases, labor costs, overhead charge, and etc will decrease. Although these numerical economics were obtained for a 10 TPD plant, these experiences indicate that the thermal plasma gasification process is a viable alternative economically if the scale increases.

Items			Costs
Construction cost			3.9 million US$
Operation cost per year	Labor costs	12 labors	0.49 million US$/year
	Depreciation cost	Depreciation period = 15 years	0.26 million US$/year
	Variable costs	Maintenance cost Electricity cost Chemical cost Wetted cost Etc	0.24 million US$/year
	Insurance	0.5% of construction cost	0.02 million US$/year
	Total		0.99 million US$/year
	Operation cost per ton of MSW	Total operation cost/330 day x 0.01 day/ton	330 US$/ton (with V.A.T.)
			300 US$/ton (without V.A.T.)

Table 8. Economic evaluation of a 10 TPD thermal plasma gasification plant for MSW treatment (These data based on the operation for 3.5 years.)

Based on this information, total construction cost for a 100 TPD scale plant would be 24.8 million US$, or 0.25 million US$/TPD. Operation cost consists of fixed cost, variable cost, and insurance. In fixed cost, labor cost, depreciation cost, and overhead charges such as fringe benefits, safe maintenance costs, training expense, and per diem and travel expenses are included; total fixed cost would be 2.39 million US$/year. Variable cost including maintenance, electricity, chemical, water costs would be 0.82 million US$/year. All of the variable costs with insurance is 0.94 million US$/year. Based on the energy balance and operational costs (Figure 10 and Table 9), profit from selling electricity generated from steam turbines would also be generated (Table 10). The recovery heat values from two steam generators are 16,679 Mcal/hr (12 plus 13 in Figure 10). Considering the total efficiency of a steam supply and power generation using a steam turbine as 26%, 4,286 Mcal/hr of electricity could be generated, which is equivalent to 5,000 kW of electricity. 2,000 kW of electricity is necessary to generate thermal plasma torches and utilities meaning that 3,000 kW of electricity could be sold to grid and is equivalent to 23.8 million kWh/year.

Considering the selling price of electricity as 10.9 cent/kWh, total profit per year from selling electricity would be around 2.6 million US$/year; the selling price of electricity recovered from MSW is relatively high compared to other electricity prices due to the government's renewable portfolio standards (RPS) policy promoting the use of renewable energy in Korea. In addition, profit could be obtained from treating MSW. 110 US$/ton is paid by the local government for treating MSW in Cheongsong, Korea, which means that, 100 TPD MSW is treated, profit for treating MSW would be 3.6 million US$/year. Therefore, total profits are 6.2 million US$/year (2.6 million US$/ year plus 3.6 million US$/ year). Considering the operation cost (3.34 million US$/year), it can be concluded that total margin for a 100 TPD MSW treatment plant using thermal plasma gasification would be about 2.86 million US$/year (6.2 million US$/year minus 3.34 million US$/year), which is equivalent to 86 US$/ton.

Based on these design parameters, energy balance, and economic evaluation, a 100 TPD thermal plasma plant for RPF (refused plastic fuel) gasification is now under construction in Yeoncheon, Korea. As soon as construction and initial operation is finished, those results will be reported.

Items				Costs
Construction cost				24.8 million US$
Operation cost per year	Fixed costs	Labor costs	14 labors	0.57 million US$/year
		Overhead charges	Fring benefits Safe maintenance cost Train expense Per diem and travel expenses Etc	0.17 million US$/year
		Depreciation cost	Depreciation period = 15 years	1.65 million US$/year
		Sub total		2.39 million US$/year
	Variable costs		Maintenance cost Electricity cost Chemical cost Wetted cost Etc	0.82 million US$/year
	Insurance		0.5% of construction cost	0.12 million US$/year
	Total			3.34 million US$/year
	Operation cost per ton of MSW		Total operation cost/330 day × 0.01 day/ton	111 US$/ton (with V.A.T.)
				101 US$/ton (without V.A.T.)

Table 9. Economic evaluations of a 100 TPD thermal plasma gasification plant for MSW treatment. These data are obtained based on experiences obtained from a 10 TPD thermal plasma gasification plant. All costs are based on Korean price. Exchange rate between USA and Korea is 1,130 won/US$.

Items	Values	Note
Power generation	5,000 kW	steam supply and power generation system
Consumed electric power	2,000 kW	
Sold electric power	3,000 kW	
Operation day per year	330 day	
Operation hour per day	24 hr	
Amount of electricity sales	23.8 million kWh/year	
Unit cost of electricity sales	10.9 cent/kWh	10.6 cent/kWh (SMP, system marginal prices) 4.4 cent/kWh (RPS, Renewable Portfolio Standards)
Profit from selling electricity	2.6 million US$/year	23,760,000 kWh/year × 10.9 cent/kWh
Profit from treating MSW	3.6 million US$/year	100 TPD × 330 day/year × 110 US$/ton (MSW treatment cost)
Total profit per ton of MSW	187 US$/ton	Total profit per year (6.2 million US$/year) /330 day × 0.01 day/ton

Table 10. Calculation of profits on the basis of used electricity, selling electricity, and treating MSW costs. These data are obtained based on experiences from a 10 TPD thermal plasma gasification plant. All costs are based on Korean price. Exchange rate between USA and Korea is 1,130 won/US$.

7. Conclusions

Thermal plasma technology is a mature, reliable, and proven method for generating high temperatures at atmospheric pressure, which is not achievable by burning fuels. Recently, thermal plasma technology has been applied for the treatment of MSW directly from trucks in pilot and commercial plants. Thermal plasma gasification processes convert organics contained in MSW into syngas, and dissociate other materials into constituent chemical elements that are then collected and vitrified to produce an inert glass-like slag retaining most of the heavy and alkali metals from the waste. The vitrified slag can be used as construction materials. In addition, NO_x and SO_x are not emitted due to O_2-starved conditions inside the thermal plasma furnace. The concentrations of dioxins are also very low compared to conventional incinerators for MSW treatment due to the high temperature of the integrated furnace. Therefore, thermal plasma processes are an environmentally friendly alternative for the gasification of MSW.

A commercial thermal plasma gasification plant for MSW was constructed at a 10 TPD scale using an integrated furnace equipped with two non-transferred thermal plasma torches, and has operated for 3.5 years without any problems. It was successfully demonstrated that the

thermal plasma process converted MSW into innocuous slag, with much lower levels of environmental air pollutant emissions and producing syngas as a potential energy source (287 Nm^3/ton for H_2 and 395 Nm^3/ton for CO), using 1.14 MWh/ton of electricity (thermal plasma torch (0.817 MWh/ton) + utilities (0.322 MWh/ton)) and 7.37 Nm^3/ton of liquefied petroleum gas (LPG). Data obtained for 3.5 years of operation provided many insights into plant operation such as economic factors and design parameters to extend capacity.

We obtained a detailed evaluation of economics for a 10 TPD scale including construction cost and operation cost. Total operation costs are 0.99 million US$/year (300 US$/ton without VAT). In addition, 110 US$/ton is paid by the local government for treating MSW. This means that total margin is negative 190 US$/ton at a 10 TPD scale. However, based on this experience, we are absolutely convinced that economics of the process will be improved if treatment scale is increased due to decrease of construction cost with increased capacity, profits from the utilization of syngas as an energy source, and the decrease of total operation costs such as labors cost and overhead charges. We also evaluated the economics for a 100 TPD thermal plasma gasification process for MSW. As a result, we calculated that total operation costs are 3.34 million US$/year (101 US$/ton without VAT) and total profits from selling electricity and treating MSW would be about 6.2 million US$/year for a 100 TPD plant, which is equivalent to 187 US$/ton. This means that total margin is positive 86 US$/ton at a 100 TPD scale.

Although the technical feasibility of thermal plasma gasification of MSW has been well demonstrated, it is not presently clear that the process is economically viable on the global market because regional variation of the costs of MSW treatment. However, it is clear that the reuse of vitrified slag and energy production from syngas will improve the commercial viability of this process, and there have been continued advances towards further development of the process.

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8. References

[1] U.S. Environmental Protection Agency (2010) Municipal solid waste in the United States: 2009 Facts and Figures. Washington, DC.

[2] N. Okafor (2011) The disposal of municipal solid wastes in environmental microbiology of aquatic and waste systems, 1 edition. Springer Science+Business Media BV.

[3] F.F. Chen (1984) Introduction to plasma physics and controlled fusion, Volume 1: Plasma physics, 2 edition. New York: Plenum Press.

[4] C. Tendero, C. Tixier, P. Tristant, J. Desmaison, P. Leprince (2006) Atmospheric pressure plasmas: A review. Spectrochim. Acta Part B 61: 2-30.

[5] A. Fridman (2008) Plasma Chemistry. New York: Chambridge University Press.

[6] J.R. Roth (1995) Industrial Plasma Engineering: Principles. Institute of Physics Publishing.

[7] H. Zhang, G. Yue, J. Lu, Z. Jia, J. Mao, T. Fujimori, T. Suko, T. Kiga (2007) Development of high temperature air combustion technology in pulverized fossil fuel fired boilers. Proc. Combust. Inst. 31: 2779-2785.

[8] U. Kogelschatz (2004) Atmospheric-pressure plasma technology. Plasma Phys. Controlled Fusion 46: B63-B75.

[9] S.-W. Kim, H.-S. Park, H.-J. Kim (2003) 100 kW steam plasma process for treatment of PCBs (polychlorinated biphenyls) waste. Vacuum 70: 59-66.

[10] Y. Cheng, M. Shigeta, S. Choi, T. Watanabe (2012) Formation Mechanism of Titanium Boride Nanoparticles by RF Induction Thermal Plasma. Chem. Eng. J. 183: 483-491.

[11] M.S. Choi, D.U. Kim, S. Choi, B.-H. Chung, S.J. Noh (2011) Iron reduction process using transferred plasma. Curr. Appl. Phys. 11: S82-S86.

[12] P. Fauchais, A. Vardelle (1997) Thermal Plasmas. IEEE Trans. Plasma Sci. 25: 1258-1280.

[13] P. Fauchais, A. Vardelle, A. Denoirhean (1997) Reactive thermal plasmas: ultrafine particle synthesis and coating deposition. Surf. Coat. Technol. 97: 66-78.

[14] P. Fauchais, M. Vardelle (1994) Plasma spraying: present and future. Pure Appl. Chem. 66: 1247-1258.

[15] T. Iwao, M. Yumoto (2006) Portable application of thermal plasma and arc discharge for waste treatment, thermal spraying and surface treatment. IEEJ T. Electr. Electr. 1: 163-170.

[16] J.P. Chu, I.J. Hwang, C.C. Tzeng, Y.Y. Kuo, Y.J. Yu (1998) Characterization of vitrified slag from mixed medical waste surrogates treated by a thermal plasma system. J. Hazard. Mater. 58: 179-194.

[17] G. Rutberg, A.N. Bratsev, A.A. Safronov, A.V. Surov, V.V. Schegolev (2002) The technology and execution of plasma chemical disnfection of hazardous medical waste. IEEE Trans. Plasma Sci. 30: 1445-1448.

[18] S.K. Nema, K.S. Ganeshprasad (2002) Plasma pyrolysis of medical waste. Curr. Sci. India 83: 271-278.

[19] T. Inaba, M. Nagano, M. Endo (1999) Investigation of plasma treatment for hazardous wastes such as fly ash and asbestos. Electr. Eng. Jpn. 126: 73-82.

[20] R. Poiroux, M. Rollin (1996) High temperature treatment of waste: From laboratories to the industrial stage. Pure Appl. Chem. 68: 1035-1040.

[21] H. Jimbo (1996) Plasma melting and useful application of molten slag. Waste Manage. 16: 417-422.

[22] K. Katou, T. Asou, Y. Kurauchi, R. Sameshima (2001) Melting municipal solid waste incineration residue by plasma melting furnace with a graphite electrode. Thin Solid Films 386: 183-188.

[23] C.-C. Tzeng, Y.-Y. Kuo, T.-F. Huang, D.-L. Lin, Y.-J. Yu (1998) Treatment of radioactive wastes by plasma incineration and vitrification for final disposal. J. Hazard. Mater. 58: 207-220.

[24] L.I. Krasovskaya, A.L. Mossé (1997) Use of electric-arc plasma for radioactive waste immobilization. J. Eng. Phys. Thermophys. 70: 631-638.

[25] International Atomic Energy Agency (IAEA) (2006) Application of thermal technologies for processing of radioactive waste.

[26] Y. Byun, M. Cho, J.W. Chung, W. Namkung, H.D. Lee, S.D. Jang, Y.-S. Kim, J.H. Lee, C.R. Lee, S.M. Hwang (2011) Hydrogen recovery from the thermal plasma gasification of solid waste. J. Hazard. Mater. 190: 317-323.

[27] Y. Byun, W. Namkung, M. Cho, J.W. Chung, Y.S. Kim, J.H. Lee, C.R. Lee, S.M. Hwang (2010) Demonstration of thermal plasma gasification/vitrification for municipal solid waste treatment. Environ. Sci. Technol. 44: 6680-6684.

[28] A. Mountouris, E. Voutsas, D. Tassios (2006) Solid waste plasma gasification: Equilibrium model development and exergy analysis. Energy Convers. Manage. 47: 1723-1737.

[29] A.S. An'shakov, V.A. Faleev, A.A. Danilenko, E.K. Urbakh, A.E. Urbakh (2007) Investigation of plasma gasification of carbonaceous technogeneous wastes. Thermophys. Aeromech. 14: 607-616.

[30] G. Galeno, M. Minutillo, A. Perna (2011) From waste to electricity through integrated plasma gasification/fuel cell (IPGFC) system. Int. J. Hydrogen Energy 36: 1692-1701.

[31] M. Minutillo, A. Perna, D.D. Bona (2009) Modelling and performance analysis of an integrated plasma gasification combined cycle (IPGCC) power plant. Energy Convers. Manage. 50: 2837-2842.

[32] J. Heberlein, A.B. Murphy (2008) Thermal plasma waste treatment. J. Phys. D: Appl. Phys. 41: 053001.

[33] S.L. Camacho (1988) Industrial worthy plasma torches: State-of-the-art. Pure Appl. Chem. 60: 619-632.

[34] J.M. Park, K.S. Kim, T.H. Hwang, S.H. Hong (2004) Three-dimensional modeling of arc root rotation by external magnetic field in non-transferred thermal plasma torches. IEEE Trans. Plasma Sci. 32: 479-487.

[35] M. Hur, S.H. Hong (2002) Comparative analysis of turbulent effects on thermal plasma characteristics inside the plasma torches with rod- and well-type cathodes. J. Phys. D: Appl. Phys. 35: 1946-1954.

[36] Juniper.com (2008) The alter NRG/Westinghouse plasma gasification process: Independent waste technology report, in, Juniper.com, Bisley, England.

[37] Solenagroup Company. Available: http://www.solenagroup.com. Accessed 2011 May 15.

[38] J. Bowyer, K. Fernholz (2010) Plasma gasification: An examination of the health, safety, and environmental records of established facilities, in, Dovetail Partners, Inc..

[39] Westinghouse-plasma Company. Available: http://www.westinghouse-plasma.com. Accessed 2011 May 20.

[40] Europlasma Company. Available: http://www.europlasma.com. Accessed 2011 May 17.

[41] Phoenixsolutions Company. Available: http://www.phoenixsolutionsco.com/psctorches.html. Accessed 2011 May 16.

[42] Tetronics Company. Available: http://www.tetronics.com. Accessed 2011 May 19.

[43] Juniper.com (2007) Plasma technologies for waste processing applications: Juniper ratings report. Bisley, England.

[44] M.J. Castaldi, N.J. Themelis (2010) The case for increasing the global capacity for waste to energy (WTE). Waste Biomass Valor. 1: 91-105.

[45] Q. Zhang, L. Dor, K. Fenigshtein, W. Yang, W. Blasiak (2012) Gasification of municipal solid waste in the plasma gasification melting process. Appl. Energy 90: 106-112.

[46] E. Leal-Quirós (2004) Plasma Processing of Municipal Solid Waste. Braz. J. Phys. 34: 1587-1593.

[47] H. Cheng, Y. Hu (2010) Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. Bioresour. Technol. 101: 3816-3824.

[48] U. Arena (2012) Process and technological aspects of municipal solid waste gasification. A review. Waste Manage. 32: 625-639.

[49] H. Nishikawa, M. Ibe, M. Tanaka, M. Ushio, T. Takemoto, K. Tanaka, N. Tanahashi, T. Ito (2004) A treatment of carbonaceous wastes using thermal plasma with steam. Vacuum 73: 589-593.

[50] D. Cyranoski (2006) One man's trash. Nature 444: 262-263.

[51] E. Dodge (2008) Plasma-gasification of waste. Clean production of renewable fuels through the vaporization of garbage. Cornell University-Johnson Graduate School of Management.